DEFINITIONS & FORMULAE FOR STUDENTS

HEAT ENGINES

RIMMER

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DEFINITIONS AND FORMULAE FOR STUDENTS

(HEAT ENGINES)

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FOURTH EDITION

LONDON
SIR ISAAC PITMAN & SONS, LTD.
PITMAN HOUSE, PARKER ST., KINGSWAY, W.C.2.
BATH MELBOURNE

1939

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PREFACE

In this booklet there will be found a number of the more important definitions and formulae used in the subject of Heat Engines, up to about the standard of work required for the Higher National Certificate. It is hoped that students will find this booklet useful, not only for general reference, but also when revising their knowledge previous to examinations, etc.

At the same time it is necessary to add a word of warning. The booklet should not be regarded as replacing existing textbooks. The definitions have been made as concise as possible, and are summaries of essential points rather than rigid and complete statements. Very little descriptive or explanatory matter has been introduced.

Further, it is not suggested that all the formulae given should be memorized. Indeed, it is necessary to avoid the habit of their slavish use. Whenever possible it is preferable to work from first principles, and while in certain circumstances the employment of a formula is legitimate, it is essential that there should be a clear grasp of the underlying principles,

even though the result is obtained by the mere substitution of numerical data. In a number of cases corresponding values in Fahrenheit and Centigrade units have been given.

The symbols and abbreviations used are those advocated by the British Standards Institution in their publication No. 560—1934, *British Standard Engineering Symbols and Abbreviations.*

A. R.

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DEFINITIONS & FORMULAE FOR STUDENTS
(HEAT ENGINES)

SECTION I
DEFINITIONS

Absolute Pressure. The sum of the gauge or indicated pressure and the atmospheric pressure. In the case of condensers it is the difference of the barometric reading and the vacuum gauge reading.

Absolute Zero of Temperature. The temperature of a perfect gas at which the volume is theoretically reduced to zero and it therefore has no heat. (A perfect heat engine having the absolute zero as its lower temperature limit would have an efficiency of unity.)

Adiabatic Operation. A change of conditions during which no heat is received from, or rejected to, external sources.

After-burning. The continuance of combustion in an internal combustion engine during the first portion of the expansion stroke.

After-cooling. The reduction in temperature of the air leaving an air compressing plant.

Angle of Advance. The angle, in excess of 90°, by which the eccentric leads the crank. (See Fig. 9.)

Avogadro's Hypothesis. Equal volumes of different gases, at the same pressure and temperature, contain the same number of molecules. (Hence the volume occupied by any gas whose mass is equal numerically to its molecular weight is a constant quantity. E.g. 2 lb. of hydrogen, 32 lb. of oxygen, 44 lb. of carbon dioxide all occupy 358 cub. ft. at S.T.P.)

Back-firing. Combustion of the mixture (in an internal combustion engine) taking place during the suction stroke.

Bleeding. The process of tapping off live steam during expansion in a compound engine or turbine and using this steam for the heating of the boiler feed water.

Boiling Point. The temperature at which the vapour pressure of a liquid becomes equal to the external pressure and the liquid passes into the state of vapour. Abbreviation: b.p.

Brake Horse-power. The effective horse-power, delivered at the crankshaft of an engine, which is available for doing external work. Abbreviation: b.h.p.

Calorific Value of a Fuel. (*a*) *Higher or Gross Value.* The amount of heat given out during the complete combustion of unit mass or unit volume of the fuel, when the products of combustion are cooled down to the original temperature of the fuel.

(*b*) *Lower or Net Value.* The amount of heat given out as above when the products of combustion are cooled but the steam formed is not condensed. (The L.C.V. is thus less than the H.C.V. by the latent heat of the steam formed, the sensible cooling below 212° F. (100° C.) being, as a rule, neglected.)

Carnot Cycle. The cycle followed in the working of a perfect heat engine, the heat being received and rejected at constant temperatures and the whole being perfectly reversible.

$$\text{Efficiency} = \frac{T_1 - T_2}{T_1}$$

Carnot's Principle. No other heat engine can be more efficient than a reversible engine, when both work between the same limits of temperature.

Clearance Volume Ratio. $\dfrac{\text{Clearance volume}}{\text{Piston-swept volume.}}$

(See also Compression Ratio.)

Coefficient of Performance. (Refrigerating machine.) $\dfrac{\text{Heat extracted}}{\text{Work expended.}}$

Combustion. The chemical combination of elements with oxygen, accompanied by the evolution of heat.

Compounding. (*a*) *Steam-engines.* The process of carrying out the total expansion of the steam in two or more cylinders in succession.

(*b*) *Impulse Steam Turbines.* The process of dividing up into stages the total drop of pressure in the turbine ("pressure compounding") or the total absorption of kinetic energy ("velocity compounding"). In the former case there will be several nozzle stages but single row wheels, while in velocity compounding the expansion is completed in a single set of nozzles, but the wheel carries two or more rows of blades.

Compression Ratio. $\dfrac{\text{Volume at beginning of compression}}{\text{Volume at end of compression}}$

$= \dfrac{\text{Piston-swept volume} + \text{Clearance volume}}{\text{Clearance volume.}}$

Abbreviation: Comp. r. Symbol: *r*.

Condition Curve. The locus of points on the Total Heat-Entropy Chart, representing the condition of steam at the beginning and end of each stage in a multi-stage steam turbine.

Conditions for Maximum Efficiency of Heat Engine Cycles. The engine must be *reversible*, i.e.

(1) Reception of all heat at highest temperature and rejection of all heat at lowest temperature.

(2) Working substance at temperature of the "source" when receiving heat and at the temperature of the "sink" when rejecting heat.

(3) All free or imperfectly resisted expansion and compression avoided.

Conduction of Heat. The transmission of heat from one part of a substance to another (or from one substance to another in contact with it) without actual transference of any part of the substance or substances.

Constant Dryness or Constant Quality Lines. Lines on a steam chart, passing through all the "state points" of equal dryness fraction.

Constant Volume Lines. Lines on a steam chart passing through all the "state points" representing an equal volume of steam (dry or wet).

Convection of Heat. The transmission of heat through a substance by actual mixing of the particles owing to the circulation set up, due principally to change of density with heating.

Critical Pressure. The particular pressure which, existing on the exhaust side of an orifice, will allow of maximum discharge through the orifice, with any given pressure on the admission side.

Critical State. The particular pressure and temperature of a substance at which the latent heat of vaporization becomes zero.

Critical Temperature. The temperature above which a substance can only exist as a gas, however great the pressure.

Cylinder Feed. The actual weight of steam supplied to either side of the piston of a steam-engine per revolution.

Dalton's Law of Partial Pressures. The pressure of a mixture of a gas and a vapour is equal to the sum of the pressures which each would exert, if it occupied the same space alone.

Detonation. The practically instantaneous ignition of an explosive mixture due to the heat produced by a pressure wave set up, in certain circumstances, when the mixture first starts to burn. It is indicated by a knock or ringing sound (usually termed "pinking") on the cylinder walls.

Diagram Factor. $\dfrac{\text{M.E.P. from actual indicator diagram}}{\text{M.E.P. from hypothetical diagram.}}$

Dissociation. The disintegration of gases into their constituents at high temperatures with absorption of heat.

Dryness Fraction of Wet Steam. The mass of pure saturated steam contained in unit mass of wet steam. Symbol: q.

Efficiency. Abbreviation: eff. Symbol: η.

Air Compressors.

Volumetric efficiency

$$= \frac{\text{Volume of air delivered per stroke reduced to "free air"}}{\text{Piston-swept volume.}}$$

$$\text{Efficiency of compression} = \frac{\text{Isothermal horse-power on air delivered}}{\text{Indicated horse-power.}}$$

Boilers.

Efficiency

$$= \frac{\text{Heat taken up by the steam per unit mass of fuel burnt}}{\text{Calorific value of fuel.}}$$

Condensers.

Vacuum efficiency

$$= \frac{\text{Actual vacuum at steam inlet to condenser}}{\text{Vacuum corresponding to minimum pressure at steam inlet.}}$$

Engines.

$$\text{Mechanical efficiency} = \frac{\text{Brake horse-power}}{\text{Indicated horse-power.}}$$

$$\text{Thermal efficiency} = \frac{\text{Heat converted into work}}{\text{Heat supplied.}}$$

Efficiency ratio or relative efficiency

$$= \frac{\text{Thermal efficiency of actual heat engine}}{\text{Thermal efficiency of ideal heat engine working on same cycle.}}$$

Volumetric efficiency (I.C. Engines)

$$= \frac{\text{Volume of mixture per suction stroke at S.T.P.}}{\text{Piston-swept volume.}}$$

Turbines.

$$\text{Nozzle or stage efficiency} = \frac{\text{Actual heat drop}}{\text{Available heat drop.}}$$

$$\text{Wheel or diagram efficiency} = \frac{\text{Energy taken up by wheel}}{\text{K.E. of steam entering wheel.}}$$

$$\text{Thermal efficiency} = \frac{\text{Actual output of turbine}}{\text{Heat supplied to turbine.}}$$

$$\text{Overall or relative efficiency} = \frac{\text{Actual output of turbine}}{\text{Adiabatic heat drop across turbine.}}$$

Enthalpy. The sum of the internal energy and the pressure energy of a substance. (*Note.* This is sometimes termed the "total heat.") Symbol I.

Entropy. The characteristic or function of the state of a substance which increases or diminishes according as the substance receives or rejects heat. (The mathematical relationship is expressed by $d\phi = \frac{dH}{T}$.) Symbol: φ.

Equivalent Eccentric. The single eccentric which would give to a slide valve the same motion as that derived from an actual valve gear (link motion or radial gear).

Equivalent Evaporation. The evaporation of a boiler, assuming it to take place "from and at" 212° F. (or 100° C.).

If H = heat supplied per lb. of steam formed

L = Latent heat of water at atmospheric pressure (in same units).

w = wt. of steam generated per lb. of coal burnt (lb.)

$$\text{Equivalent evaporation} = \frac{w \times H}{L} \text{ lb.}$$

Evaporative Value of a Fuel. $\dfrac{\text{Calorific value of fuel}}{\text{Latent heat of water.}}$

Factor of Evaporation. $\dfrac{\text{Heat supplied per lb. of steam generated}}{\text{Latent heat of water.}}$

Flash Point of Oil. The temperature at which the oil begins to give off inflammable vapour sufficiently freely to form an explosive mixture (either in a "closed" or "open" space).

Forced Draught. The forcing of air, by means of a fan, into a closed stokehold so that the air can only pass to the chimney via the furnace and fuel bed.

Free Air. The volume of air delivered by an air compressor, when expanded to atmospheric pressure and temperature.

Freezing Point. The temperature at which a liquid solidifies.

Friction Horse-power. The difference between the indicated horse-power and the brake horse-power of an engine.

Fuel. A substance suitable (by its combination with oxygen) for the rapid and economical supply of heat for industrial purposes.

Heat Drop. The difference between the heat contained in the working fluid at any two points in a heat engine cycle. Symbol: DH or Δ.

Heat Engine. A machine which enables mechanical work to be done through the agency of heat energy, usually by changes of volume of a "working fluid."

Indicated Horse-power. The horse-power of an engine as determined from the mean indicator diagram. Abbreviation: i.h.p.

Indicated Steam. The difference between the steam present at cut-off and that present during cushioning (as determined from the indicator diagram).

Induced Draught. The drawing of air through the furnace and fuel bed of a boiler by means of a fan situated beyond the boiler.

Intercooling. The reduction in temperature (usually approximating to initial conditions) between the stages of an air compressor.

Internal Energy. The heat energy of a substance by virtue of which it can do work.

Isentropic Operation. A change of conditions during which the entropy remains constant.

Isothermal Operation. A change of conditions during which the temperature remains constant.

Joule-Thomson Effect. The slight cooling $\left(\frac{\text{Drop of temperature}}{\text{Drop of pressure}}\right)$ which takes place when a gas expands through a porous plug without doing work.

Lap. (*a*) *Steam* (*or outside*) *Lap.* The amount by which a slide valve overlaps the steam port, on the admission side, when the valve is in mid-position.

(*b*) *Exhaust* (*or inside*) *Lap.* The amount by which a slide valve overlaps the steam port, on the exhaust side, when the valve is in mid-position. (See Fig. 9.)

Latent Heat. The portion of the heat supplied to a substance which produces change of state without change of temperature. Abbreviation: lat. ht. Symbol: *l* or L.

Laws of Perfect Gases. (1) *Boyle's Law.* Volume of gas inversely proportional to the pressure, if the temperature is constant.

(2) *Charles's Law.* (*a*) Volume of gas proportional to the absolute temperature, if the pressure is constant. (*b*) Pressure of gas proportional to the absolute temperature, if the volume is constant.

(3) *Joule's Law.* The internal energy of a given quantity of gas depends only on its temperature and is independent of its pressure and volume.

Laws of Thermodynamics. (1) Heat and work are mutually convertible and "Joule's Equivalent" (J) measures the rate of exchange. (See also Mechanical Equivalent of Heat.)

(2) Heat will not pass up from a colder to a hotter body, *of its own accord.*

Lead. The amount by which the steam port is uncovered by the slide valve when the piston of a steam-engine is just beginning its stroke. (See Fig. 9.)

Mean Effective Pressure. The average pressure exerted by the working fluid on the piston of an engine, during one stroke. Abbreviation: m.e.p.

Mechanical Equivalent of Heat. The number of units of work which are equivalent to one unit of heat. Symbol: J.

778 ft. lb. = 1 B.Th.U.
1,400 ft. lb. = 1 C.H.U.

Melting Point. The temperature at which a solid liquefies.

Missing Quantity. The difference between the "cylinder feed" and the "indicated steam" per stroke of a steam-engine.

Molecular Volume ("Mol"). The volume occupied by the molecular weight of a gas. It is 358 cu. ft. when the weight is expressed in lb. and 22,310 c.c. when the weight is expressed in grammes (both at S.T.P.).

Premature Ignition. The ignition of the mixture, in an internal combustion engine, taking place before the correct point on the compression stroke.

Priming. The carrying over of particles of water in the steam flowing from a boiler.

Radiation. The transmission of heat through space by wave motion.

Rankine Cycle. A modified Carnot cycle, used as the standard of comparison of actual steam-engine and turbine performance. (See Steam-engine formulae.)

Ratio of Expansion. (Steam-engine.)

$$\text{Nominal ratio of expansion} = \frac{\text{Total piston-swept volume}}{\text{Piston-swept volume at cut-off.}}$$

$$\text{True ratio of expansion} = \frac{\text{Total piston-swept volume} + \text{Clearance volume}}{\text{Piston-swept volume at cut-off} + \text{Clearance volume.}}$$

Refrigeration. The process of extracting heat from a body at low temperature and transferring this heat, by the expenditure of mechanical work, to a body at a higher temperature.

Regenerative Feed Heating. See "Bleeding."

Re-heat Factor. (Multi-stage steam turbines.)

$$= \frac{\text{Cumulative heat drop}}{\text{Adiabatic heat drop.}}$$

Symbol: R.

(*Note.* Cumulative heat drop = Sum of successive heat drops.)

Reversible Heat Engine. A heat engine which will convert a certain quantity of heat (H) into an amount of work (W), and if the same amount of work (W) is expended in driving the engine backwards will produce the original quantity of heat (H).

Reversible Process. A process which may be performed in either direction, initial and final states of the working fluid being the same.

Saturated Steam. Steam which has the same temperature and pressure as the water from which it is formed.

Sensible Heat. The portion of the heat supplied to a substance which produces changes of temperature without change of state.

Specific Heat. The amount of heat (or mechanical work) required to raise unit mass of a substance one degree of temperature. Abbreviation: sp. ht.

(*Note.* In the case of gases there are two specific heats, according as to whether the heating takes place at constant pressure or at constant volume. Also it is very usual to refer them to unit volume. See "volumetric heat.")

Stefan's Law. The rate at which heat is radiated from a perfect radiator is proportional to the fourth power of its absolute temperature.

Superheated Steam. Steam which has a temperature above that corresponding to its pressure.

Supersaturated or Supercooled Steam. Steam which has a temperature below that corresponding to its pressure.

Throttling. The expansion of a fluid through a constricted passage (across which there is a pressure difference), during which no external work is done, the initial and final velocities of the fluid are equal, and there is no reception of heat from, or rejection of heat to, external sources (though there will be a change of entropy).

Toluene Value. A measure of the detonating tendencies of a petrol, defined as the percentage of toluene (C_7H_8) which must be added to "standard aromatic free petrol" to produce the same tendency to detonate as that of the fuel considered.

Total Energy of a Fluid. The sum of its internal (or heat) energy, its pressure energy and its kinetic energy.

Total Heat of a Substance. The sum of its sensible and latent heats and superheat (if any). Symbol: H.

Travel of a Slide Valve. The distance moved by a slide valve between its two extreme positions. (Half travel = steam lap + maximum opening to steam.) (See Fig. 9.)

Uniflow Engine. An engine in which steam flows in only one direction in each half of the cylinder being exhausted through a ring of ports situated at the centre of the cylinder.

Unit of Heat. The quantity of heat required to raise unit mass of water through one degree of temperature.

Universal Gas Constant. The product of the molecular weight of a gas and the value of the term K in the characteristic equation of the gas ($PV = KT$). It represents the change of energy per degree change of temperature. Symbol: R.

Vapour. A fluid which does not entirely conform to the laws of perfect gases, being in a state below its critical temperature.

Velocity Coefficient. (Steam turbines.)

$$= \frac{\text{Relative velocity of steam to blades at outlet}}{\text{Relative velocity of steam to blades at inlet.}}$$

Viscosity. A measure of the fluidity of an oil, in comparison with that of a standard oil, based on the time of outflow through a certain orifice under specified conditions.

Volumetric Heat. The heat required to raise unit volume of a gas through one degree of temperature.

Willan's Lines. Straight lines obtained by plotting steam consumption against horse-power of a steam-engine running at uniform speed and having a constant cut-off.

Wilson Line. A curve which may be applied to the Total Heat-Entropy Chart to indicate the limit of supersaturated expansion.

SECTION II

FORMULAE

GENERAL SYMBOLS

P = pressure (lb. per sq. ft.).
p = pressure (lb. per sq. in.).
V = volume (cu. ft.).
M = molecular weight.
t = ordinary temperature (° F. or ° C.).
T = absolute temperature (° F. or ° C.).
m = mass of gas or other fluid (lb.).
K = constant (units of work or heat).
c_p = specific heat at constant pressure.
c_v = specific heat at constant volume.
J = Joule's Equivalent.
$A = \frac{1}{J}$.
r = ratio of expansion or compression.
ϕ = entropy.
h = sensible heat.
L = latent heat.
H = total heat.
q = dryness fraction.
c_m = mean specific heat of superheated steam over any range of temperature.
F_m = mass flow of steam.
V_w = specific volume of water.
V_s = specific volume of steam.
E_L = external latent heat.
ρ = internal latent heat.
E = internal energy.
I = enthalpy.
$DH\phi$ = adiabatic heat drop.
DH = actual heat drop.
v_i = absolute steam velocity at inlet.
v_o = absolute steam velocity at outlet.
v_{ri} = relative steam velocity at inlet.
v_{ro} = relative steam velocity at outlet.
u = blade velocity.
v_w = velocity of whirl.
α = nozzle angle (degrees).
θ_i = inlet angle of blades (degrees).
θ_o = outlet angle of blades (degrees).
ρ = $\frac{\text{blade speed}}{\text{steam speed}}$
k = blade velocity coefficient
$= \frac{v_{ro}}{v_{ri}}$.

USEFUL CONSTANTS

	Density (lb. per cu. ft.)	Specific Volume (cu. ft. per lb.)
Hydrogen (at S.T.P.)	0·00559	178·8
Air (at S.T.P.) . .	0·0807	12·39

N.T.P. 14·7 lb. per sq. in. and 60° F (15° C)
S.T.P. 14·7 lb. per sq. in. and 32° F (0° C)

(Note. In some cases " N.T.P." signify the latter condition)

Absolute temperature = T = t + 459·6 on Fahrenheit scale
= t + 273·1 on Centigrade scale.

Atmospheric pressure = 14·7 lb. per sq. in. = 1·03 kg. per sq. cm.

1 cu. ft. water weighs 62·4 lb. (at 50° F.).

1 in. water is equivalent to a pressure of 0·036 lb. per sq. in.

1 in. mercury ,, ,, ,, 0·49 lb. ,, ,,

1 British horse-power = 550 ft.-lb. per sec. = 746 watts.

1 B.Th.U. is equivalent to 778 ft.-lb.
1 C.H.U. ,, ,, ,, 1400 ft.-lb.
1 kilo-calorie ,, ,, ,, 426·8 kg.-m.
1 h.p. per hr. ,, ,, ,, 2545 B.Th.U. or 1414 C.H.U.

1 in. = 2·54 cm. | 1 metre = 39·37 in.
1 lb. = 453·6 g. | 1 kg. = 2·2 lb.
1 ft.-lb. = 0·138 kg.-m. | 1 kg.-m. = 7·23 ft.-lb.
1 B.Th.U. = 252 g.-cal. | 1 kilo calorie = 3·97 B.Th.U.

1 B.Th.U. per lb. = 0·5556 g.-cal per g.
1 B.Th.U. per cu. ft. = 8·896 g.-cal. per litre.

GASES

Energy Equation. Heat supplied or rejected = Change of internal energy + Work done.

Molecular Volume. 358 cu. ft. (mass in lb.) } At
22,310 c.c. (mass in g.) } S.T.P.

Characteristic Equation. $PV = mKT$.

$$K = \frac{14{\cdot}7 \times 144 \times 358}{491{\cdot}6 \times \text{Mol. Wt.}} = \frac{1544}{\text{Mol. Wt.}} \text{ (° F.).}$$

$$= \frac{2780}{\text{Mol. Wt.}} \text{ (° C.).}$$

Universal Gas Constant (M.K.). 1544 ft.-lb. = 1·985 B.Th.U. (° F.).
2780 ft.-lb. = 1·985 C.H.U. (° C.).

Specific Heats. $K = c_p - c_v$ $\qquad \frac{c_p}{c_v} = \gamma$

$$\frac{K}{C_v} = \gamma - 1 \qquad c_v = \frac{K}{\gamma - 1}$$

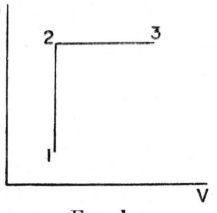


FIG. 1

Heating at Constant Volume.

Heat supplied per lb. $= c_v(T_2 - T_1)$
Work done $= 0$
Change of internal energy per lb. $= c_v(T_2 - T_1)$

Heating at Constant Pressure.

Heat supplied per lb. $= c_p(T_3 - T_2)$.
Work done $= \frac{P}{J}(V_3 - V_2)$.
Work done per lb. $= K(T_3 - T_2)$
Change of internal energy per lb. $= c_p(T_3 - T_2) - K(T_3 - T_2)$
$= c_v(T_3 - T_2)$.

Expansion or Compression (from P_1, V_1, T_1 to P_2, V_2, T_2).

(1) Equation of expansion or compression curve, $PV^n = C$.

The greater the value of n the steeper the slope of the curve.

$$\frac{P_1}{P_2} = \left(\frac{V_2}{V_1}\right)^n \qquad \left(\frac{V_2}{V_1}\right) = \left(\frac{P_1}{P_2}\right)^{\frac{1}{n}}$$

$$\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{n-1} \qquad \left(\frac{T_1}{T_2}\right) = \left(\frac{P_1}{P_2}\right)^{\frac{n-1}{n}}$$

$$\text{Work done} = \frac{P_1V_1 - P_2V_2}{n-1} \text{ ft.-lb.} = \frac{K(T_1 - T_2)}{n-1} \text{ ft.-lb. per lb.}$$

Change of internal energy per lb. $= c_v(T_2 - T_1)$.

For an adiabatic operation $n = \gamma = \dfrac{c_p}{c_v}$.

In this case heat supplied or rejected is zero and change of internal energy is numerically equal to work done but of opposite sign.

(2) Equation of expansion or compression curve $PV = C$ (isothermal).

$$P \propto \frac{1}{V} \qquad T \text{ is constant}$$

Work done $= P_1V_1 \log_e r$ ft.-lb. $= KT_1 \log_e r$ ft.-lb. per lb.

Change of internal energy $= 0$ (temperature constant).

Heat Reception or Rejection ($PV^n = C$).

Rate of heat reception or rejection

$$= \frac{dH}{dV} = \frac{P}{J} \times \frac{\gamma - n}{\gamma - 1} \text{ heat units.}$$

Heat received or rejected per sec.

$$= \frac{P}{J} \times \frac{\gamma - n}{\gamma - 1} \times \text{Piston-swept volume per sec.}$$

$$= \frac{\gamma - n}{\gamma - 1} \times \text{Work done per sec.}$$

Change of Entropy.

Change of state from P_1, V_1, T_1 to P_2, V_2, T_2.

$$\phi_2 - \phi_1 = c_v \log_e \frac{T_2}{T_1} + K \log_e \frac{V_2}{V_1}$$

$$= c_v \log_e \frac{P_2}{P_1} + c_p \log_e \frac{V_2}{V_1}$$

$$= c_p \log_e \frac{T_2}{T_1} - K \log_e \frac{P_2}{P_1}$$

Change of state—

At constant pressure: $\phi_2 - \phi_1 = c_p \log_e \frac{V_2}{V_1} = c_p \log_e \frac{T_2}{T_1}$

At constant volume: $\phi_2 - \phi_1 = c_v \log_e \frac{P_2}{P_1} = c_v \log_e \frac{T_2}{T_1}$

At constant temperature: $\phi_2 - \phi_1 = K \log_e \frac{V_2}{V_1} = -K \log_e \frac{P_2}{P_1}$

According to law $PV^n = C$: $\phi_2 - \phi_1 = K \frac{\gamma - n}{\gamma - 1} \log_e \frac{V_2}{V_1}$

$$= c_v \frac{\gamma - n}{n - 1} \log_e \frac{T_1}{T_2}.$$

Carnot Cycle. (Working fluid a perfect gas.)

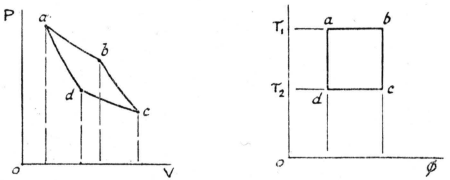


FIG. 2

Heat taken in at temperature $T_1 = Q_1$

Heat rejected at temperature $T_2 = Q_2$

$$\frac{Q_1}{T_1} = \frac{Q_2}{T_2} \qquad \text{Thermal efficiency} = \frac{T_1 - T_2}{T_1}$$

INTERNAL COMBUSTION ENGINES

Otto Cycle

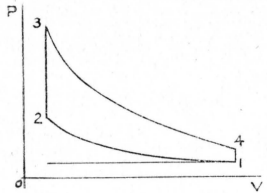


FIG. 3

Compression ratio $= r = \frac{V_1}{V_2}$

"Air standard" efficiency

$$= 1 - \left(\frac{1}{r}\right)^{\gamma - 1}$$

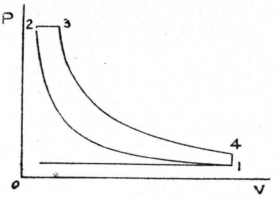


FIG. 4

Diesel Cycle.

Thermal efficiency

$$= \frac{c_p (T_3 - T_2) - c_v (T_4 - T_1)}{c_p (T_3 - T_2)}$$

(For air $c_p = 0{\cdot}2375$,
$c_v = 0{\cdot}169$, $\gamma = 1{\cdot}405$.)

STEAM AND STEAM-ENGINES

Saturated Steam	Dry	Wet
Sensible heat	h	h
Latent heat	L	qL
Total heat	h + L	$h + q$L
Specific volume	V_s	$qV_s + (1 - q)\,V_w$ $= qV_s$ (approx.)
External latent heat (E_L)	$\frac{P}{J}(V_s - V_w)$	$\frac{P}{J} q\,(V_s - V_w)$
Internal latent heat (ρ)	$L - \frac{P}{J}(V_s - V_w)$	$qL - \frac{P}{J} q\,(V_s - V_w)$
Internal energy (E)	$h + \rho = H - E_L$	$h + qL - \frac{P}{J} q\,(V_s - V_w)$
Enthalpy (I)	$E + \frac{P}{J} V_s = H + \frac{P}{J} V_w$	$h + qL + \frac{P}{J} V_w$

Specific Volume.

Saturated Steam. Clapeyron's equation $V_s = V_w + \frac{JL}{T} \cdot \frac{dT}{dP}$

Wet Steam. Callendar's equation $V = \frac{\text{Volume factor}}{p} (H - st_o)$

$(t_o = t - 32,\ s = 1 - \frac{1}{300})$.

Saturated, Superheated or Supersaturated Steam.

Callendar's equations—

(1) $V = \frac{KT}{AP} + b - \frac{c}{1 - z^2 p^2}$

b = "co-volume" = − 0·0028

c = "co-aggregation volume" = $0{\cdot}4213 \left(\frac{671{\cdot}6}{T}\right)^{\frac{10}{3}}$ (° F.)

$K = 0{\cdot}11012.\ z = 4{\cdot}0115 \frac{c}{T} = 0{\cdot}4213 \left(\frac{373{\cdot}1}{T}\right)^{\frac{10}{3}}$ (°C.)

(2) $V = \frac{1{\cdot}2464}{p} (H - 835{\cdot}2) - 0{\cdot}0021$ (H in B.Th.U.)

$= \frac{2{\cdot}2436}{p} (H - 464) - 0{\cdot}0021$ (H in C.H.U.).

Van der Waal's equation for any fluid passing through various states—

$$\left(P + \frac{a}{V^2}\right)(V - b) = KT.$$

(a and b are constants determined by experiment.)

Adiabatic Expansion of Steam.

Steam initially dry or with dryness fraction q—

$PV^n = C$ and $n = 1{\cdot}035 + 0{\cdot}1q$ (Zeuner's equation).

Adiabatic Expansion of Steam (*contd.*)

Steam superheated or supersaturated and remaining dry during expansion—

$$\frac{P}{T^{\frac{1}{3}}} = \text{constant.} \qquad P(V - b)^{1\cdot3} = \text{constant.}$$

Steam Jacketing.

Steam kept dry and saturated during expansion—

$$PV^{\frac{17}{16}} = \text{constant.}$$

Separating Calorimeter.

W = weight of steam passing through jacket during test.

w = weight of water separated in same time.

$$\text{Dryness fraction} = \frac{W}{W + w}.$$

Throttling Calorimeter.

$$h_1 + q_1 L_1 = H_2 + c_m (t_3 - t_2) = H_2'.$$

(*Note.* The steam after expansion must be superheated. Since the pressure after throttling is about atmospheric, the mean specific heat of superheated steam (c_m) may be taken as 0·48. Preferably H_2' may be taken direct from Steam Tables.)

Separating and Throttling Calorimeter.

A = weight of wet steam.

b = weight of water extracted in separator.

q_1 = dryness fraction determined in throttling calorimeter.

c = weight of water in steam passing through throttling calorimeter = $(A - b)(1 - q_1)$.

Dryness fraction of steam in main pipe $= q = \dfrac{A - (b + c)}{A}$

$$= \frac{q_1 (A - b)}{A}.$$

Temperature-Entropy Chart.

Specific heat of water assumed = 1 and entropy reckoned above 32° F.

Process	Change of Entropy	State Point
Heating of water from 492° F. abs. to T_1	$\phi_{w1} = \log_e \frac{T_1}{492}$	
Heating of water from 492° F. abs. to T_2	$\phi_{w2} = \log_e \frac{T_2}{492}$	c
Evaporation of water into dry steam at T_2	$\phi_{e2} = \frac{L_2}{T_2}$	d
Evaporation of water into steam of dryness fraction q_2 at T_2 . . .	$q_2\phi_{e2} = \frac{q_2 L_2}{T_2}$	m
Superheating of steam from T to T_3 .	$\phi_{h3} = c_m \log_e \frac{T_3}{T_2}$	e

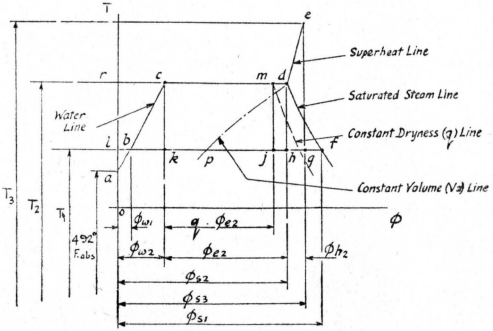


FIG. 5

Temperature-Entropy Chart (*contd.*).

Gibb's function or water potential G_1 = area $alb = T_1\phi_{w1} - h_1$

G_2 = area $arc = T_2\phi_{w2} - h_2$

Adiabatic Expansion (between temperatures T_2 (or T_3) and T_1).

Initial Condition	State Point	Expansion Line	Dryness Fraction after Expansion
Wet	m	mj	$\frac{bj}{bf} = \frac{q\phi_{e2} + \phi_{w2} - \phi_{w1}}{\phi_{s1} - \phi_{w1}}$
Dry and saturated . .	d	dh	$\frac{bh}{bf} = \frac{\phi_{s2} - \phi_{w1}}{\phi_{s1} - \phi_{w1}}$
Superheated . .	e	eg	$\frac{bg}{bf} = \frac{\phi_{s3} - \phi_{w1}}{\phi_{s1} - \phi_{w1}}$

Initial Condition	Adiabatic Equation
Wet . .	$\frac{q_1L_1}{T_1} = \log_e \frac{T_2}{T_1} + \frac{q_2L_2}{T_2}$
Dry and saturated .	$\frac{q_1L_1}{T_1} = \log_e \frac{T_2}{T_1} + \frac{L_2}{T_2}$
Superheated .	$\frac{q_1L_1}{T_1} = \log_e \frac{T_2}{T_1} + \frac{L_2}{T_2} + c_m \log_e \frac{T_3}{T_2}$

Temperature-Entropy Chart (*contd.*).

Constant Volume Line.

If V_1 and V_2 are specific volumes at T_1 and T_2 respectively

$$\frac{bp}{bf} = \frac{V_2}{V_1}.$$

Total Heat-Entropy Chart.

This chart gives a ready means of determining the "condition" of

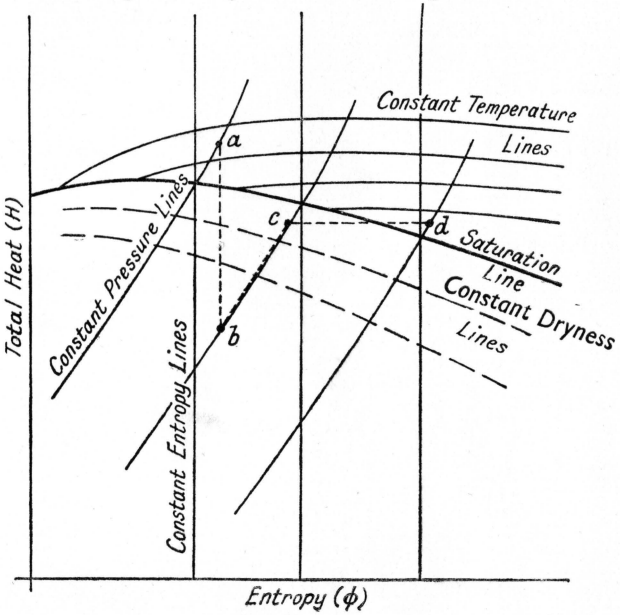


FIG. 6

steam and has the advantage that the quantities of heat are represented by lengths, whereas on the T — ϕ chart they are represented by areas. (See Fig. 6.)

ab represents adiabatic expansion.

bc represents reheating at constant pressure.

cd represents throttling to a lower pressure (heat content constant).

Rankine Cycle.

P–V. Diagram.

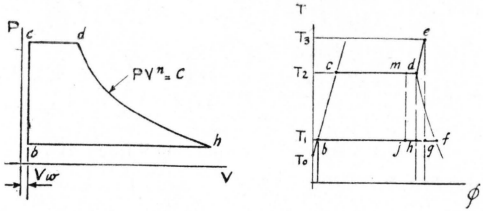


FIG. 7

Thermal efficiency (saturated steam)

$$\frac{P_d V_d + \dfrac{P_d V_d - P_h V_h}{n-1} - P_h V_h - (P_d - P_h) V_w}{J (H_2 - h_1)}$$

(V_w = volume of feed water and is a very small term which may generally be neglected.)

(Value of n will vary according to initial conditions.)

Rankine Cycle (*contd.*).

T–ϕ **Diagram.**

Initial Condition	Thermal Efficiency
Wet . .	$\dfrac{(h_2 + q_2L_2 - h_1) - q_1L_1}{h_2 + q_2L_2 - h_1} = 1 - \dfrac{T_1\left(\log_e \dfrac{T_2}{T_1} + \dfrac{q_2L_2}{T_2}\right)}{(T_2 - T_1) + q_2L_2}$
Dry and Saturated .	$\dfrac{(H_2 - h_1) - q_1L_1}{H_2 - h_1} = 1 - \dfrac{T_1\left(\log_e \dfrac{T_2}{T_1} + \dfrac{L_2}{T_2}\right)}{(T_2 - T_1) + L_2}$
Superheated .	$\dfrac{(H_3 - h_1) - q_1L_1}{H_3 - h_1} = 1 - \dfrac{T_1\left(\log_e \dfrac{T_2}{T_1} + \dfrac{L_2}{T_2} + c_m \log_e \dfrac{T_3}{T_2}\right)}{(T_2 - T_1) + L_2 + c_m (T_3 - T_2)}$

See also " Adiabatic Expansion " (page 19).

Theoretical M.E.P.

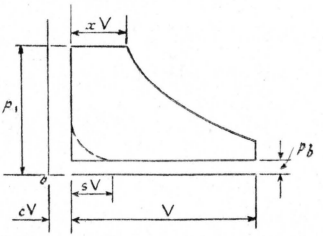


FIG. 8

(1) **Clearance Neglected.** ("Hypothetical" Diagram.)

Ratio of expansion $= r = \dfrac{1}{x}$

Law of Expansion Curve	M.E.P. (p_m)
$PV^n = C$	$\frac{p_1}{n-1}\left(nx - \frac{1}{r^n}\right) - p_b$
$PV = C$	$\frac{p_1}{r}(1 + \log_e r) - p_b$

(2) Clearance Considered.

Ratio of expansion $= R = \frac{1+c}{x+c} = \frac{r(1+c)}{1+cr}$.

Law of Expansion Curve	M.E.P. (p_m)
$PV^n = C$	$\frac{p_1}{n-1}\left(nx + c - \frac{1+c}{R^n}\right) - p_b$
$PV = C$	$p_1 x + p_1 (x + c) \log_e R - p_b$ $= \left[\frac{p_1}{R}(1 + \log_e R) - p_b\right][1 + c] - c(p_1 - p_b)$
$PV = C$ and considering cushioning (dotted line)	$p_1 x + p_1 (x + c) \log_e R$ $- p_b (1 - s) - p_b (s + c) \log_e \frac{s + c}{c}$

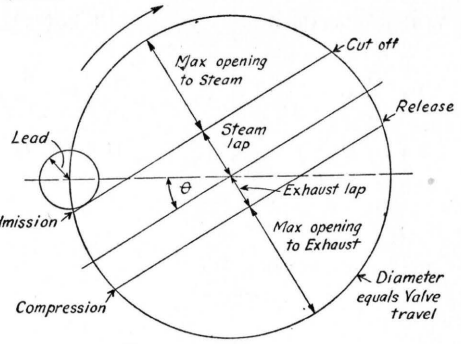
Compound Expansion.

R = Total ratio of expansion.
r = Ratio of expansion in high pressure cylinder.
L = Ratio of cylinder volumes.
p_r = Receiver pressure.

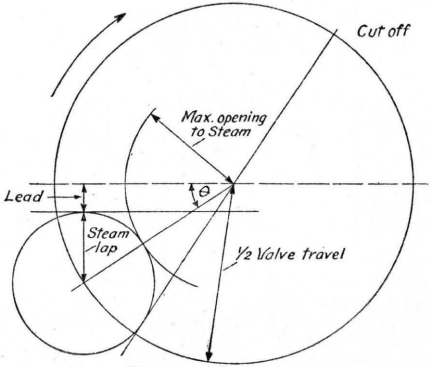
$$R = rL$$

For equal initial loads on pistons $(p_1 - p_r) = L(p_r - p_b)$.

Valve Diagrams.



REULEAUX DIAGRAM



BILGRAM DIAGRAM

FIG. 9

Regenerative Feed Heating (" Bleeding ").

w = weight of steam to be tapped from the turbine or engine receiver to heat the feed water to corresponding temperature—

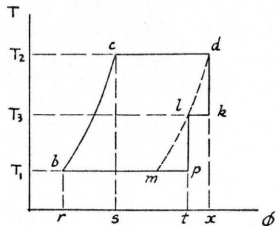


FIG. 10

$$w = \frac{\dfrac{T_3 - T_1}{T_3}}{\log_e \dfrac{T_2}{T_3} + \dfrac{L_2}{T_2}} = \frac{\dfrac{h_3 - h_1}{T_3}}{\phi_{s2} - \phi_{w3}}$$

Efficiency

$$= 1 - \frac{1}{1 + w} \cdot \frac{T_1 \left(\log_e \dfrac{T_2}{T_1} + \dfrac{L_2}{T_2} \right)}{T_2 - T_3 + L_2}$$

$$= 1 - \frac{1}{1 + w} \cdot \frac{T_1 (\phi_{s2} - \phi_{w3})}{H_2 - h_3}$$

Rankine cycle efficiency for the same range of temperature

$$= 1 - \frac{T_1 (\phi_{s2} - \phi_{w1})}{H_2 - h_1}$$

(In practice the steam is usually "bled" or tapped off at two or more points and the drains for the feed heaters "cascaded" to the condenser).

STEAM TURBINES

Equation of Steady Flow of a Fluid.

$$I_1 - I_2 + \frac{v_1^2 - v_2^2}{2gJ} = \text{Work done per lb.} + \text{Heat lost to external bodies.}$$

(Suffixes 1 and 2 refer to initial and final conditions).

Orifice.

Pressure drop P_1 to P_2. Area = A sq. ft.

$$\text{Velocity of steam} = \sqrt{2g\frac{n}{n-1}\,P_1V_1\left\{1-\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}\right\}}\ \text{f.p.s.}$$

$$= \sqrt{2g\,J \times \text{Rankine heat drop}}$$

$$= 223{\cdot}8\sqrt{I_1 - I_2}. \quad (I \text{ in B.Th.U.})$$

$$= 300{\cdot}2\sqrt{I_1 - I_2}. \quad (I \text{ in C.H.U.})$$

$$\text{Discharge} = m \text{ lb. per sec.} = A\sqrt{2g\frac{n}{n-1}\frac{P_1}{V_1}\left\{\left(\frac{P_2}{P_1}\right)^{\frac{2}{n}}-\left(\frac{P_2}{P_1}\right)^{\frac{n+1}{n}}\right\}}$$

$$= \frac{\text{Area} \times \text{Velocity}}{\text{Volume per lb. steam}}$$

$$\text{For maximum discharge } \frac{P_2}{P_1} = \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}}$$

Initial Condition	n	$\frac{P_2}{P_1}$	Max. Velocity (f.p.s.)	Max. Discharge (lb. per sec.)
Dry and saturated	1·135	0·577	$70{\cdot}21\sqrt{p_1V_1}$	$0{\cdot}3003a\sqrt{\frac{p_1}{V_1}}$
Superheated or supersaturated	1·3	0·546	$72{\cdot}4\sqrt{p_1V_1}$	$0{\cdot}3155a\sqrt{\frac{p_1}{V_1}}$

(Note a = area of orifice in sq. in.)

Nozzle.

To discharge w lb. per sec. assuming *saturated* steam and adiabatic flow.

	Pressure	Dryness Fraction	Enthalpy	Velocity of Steam	Area (sq. ft.)
Entrance	p_1	q_1	I_1		
Throat	$p_2 = 0{\cdot}577p_1$	q_2	I_2	$v_2 = 223{\cdot}8\sqrt{I_1 - I_2}$	$\frac{w \cdot q_2V_{s2}}{v_2}$
Exit .	p_3	q_3	I_3	$v_3 = 223{\cdot}8\sqrt{I_1 - I_3}$	$\frac{w\,q_3V_{s3}}{v_3}$

(Dryness fractions and total heats determined from Steam Tables or Charts, according to initial conditions. For superheated steam $p_2 = 0{\cdot}546p_1$. If heat drops in C.H.U replace 223·8 by 300·2.)

Impulse Turbines.

If F_m = mass flow of steam (lb. per sec.),

Work done per lb. of steam $= \dfrac{uv_w}{g}$ ft.-lb.

Energy loss in blades $= \dfrac{v_1^2}{2g} - \dfrac{uv_w}{g} - \dfrac{v_o^2}{2g}$

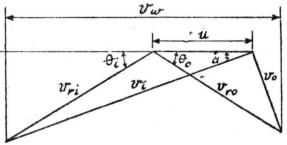


FIG. 11

$$\text{Diagram efficiency} = \frac{\text{Work done}}{\text{Initial K.E.}} = 2\frac{uv_w}{v_1^2} = \frac{\text{Horse-power}}{\text{DH}}$$

$$\text{Nozzle or stage efficiency} = \frac{\text{DH}}{\text{DH}\phi}.$$

$$\text{Thermal efficiency} = \frac{\text{H.p.} \times 0{\cdot}707}{F_m(\text{Heat supplied per lb.})}$$

$$\text{Overall or relative efficiency} = \frac{\text{H.p.} \times 0{\cdot}707}{F_m \times \text{DH}\phi}.$$

If n = number of stages $\quad \rho = \dfrac{\text{Blade speed}}{\text{Steam speed}} = \dfrac{u}{v_1}$.

For maximum efficiency $\rho = \dfrac{\cos\alpha}{2n}$.

Impulse Turbines (*contd.*).

Conditions	Maximum Efficiency
Blading symmetrical and friction neglected .	$\cos^2\alpha$
Blading symmetrical and friction considered .	$(1 + k)\frac{\cos^2\alpha}{2}$
Blading not symmetrical and friction considered	$\left(1 + k\frac{\cos\theta_o}{\cos\theta_i}\right)\frac{\cos^2\alpha}{2}$

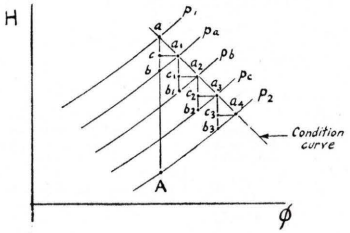


FIG. 12

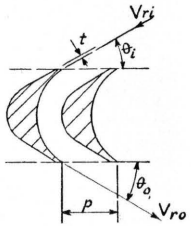


FIG. 13

Stage efficiency $= \eta_s = \dfrac{ac}{ab}$.

Reheat factor $= \mathrm{R} = \dfrac{\Sigma ab}{a\mathrm{A}}$.

$$\text{Internal efficiency} = \frac{\text{Work done on rotor per lb steam}}{\text{Adiabatic heat drop}}$$

$$= \frac{\Sigma ac}{a\mathrm{A}} = \frac{\Sigma \eta_s \times ab}{a\mathrm{A}} = \eta_s \times \mathrm{R}.$$

(If η_s is the same for all stages.)

Impulse Turbines (*contd.*)

HEIGHT OF BLADING.

F_m = mass flow of steam (lb. per sec.).
D = mean diameter of wheel (inches).
h = height of blades (inches).
p = pitch of blades (inches).
t = thickness of blades at tips (inches).
n = number of blades covered by each nozzle.

$$V_{ro} \times nh\,(p \sin \theta_o - t) = F_m \times V_s \times 144.$$

Reaction Turbines.

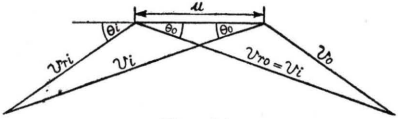


FIG. 14

Owing to expansion taking place in moving blades as well as in fixed ones, kinetic energy is generated in the former also, giving rise actually to an impulse-reaction effect. Normally the inlet and outlet angles of both fixed and moving blades are the same (35° and 20°) and $v_{ro} = v_i$.

For maximum efficiency $\rho = \cos \alpha$. ($\alpha = \theta_0 =$ outlet angle of fixed and moving blades.)

Blades are usually sharp and t may be neglected.

$$V_{ro} \times nph \sin \theta_o = F_m \times V_s \times 144.$$

With all round admission $np = \pi D$.

COMBUSTION AND HEAT TRANSMISSION

Elements.

Name	Hydrogen	Carbon	Nitrogen	Oxygen	Sulphur
Chemical symbol .	H	C	N	O	S
Atomic weight .	1	12	14	16	32

Compounds.

Name	Water or Steam	Carbon Mon-oxide	Carbon Di-oxide	Sulphur Di-oxide	Methane or Marsh Gas	Ethylene or Olefiant Gas
Chemical formula .	H_2O	CO	CO_2	SO_2	CH_4	C_2H_4
Molecular weight . .	18	28	44	64	16	28

Composition of Air.

	Oxygen	Nitrogen
By weight . . .	23%	77%
By volume . . .	21%	79%

Specific Heats at Ordinary Temperatures. (Water = 1·0)

Air, nitrogen and carbon monoxide . . .	0·24
Oxygen and carbon dioxide	0·22
Steam	0·48

Chemical Equations.

$$C + O_2 = CO_2$$
$$2C + O_2 = 2CO$$
$$2CO + O_2 = 2CO_2$$
$$S + O_2 = SO_2$$
$$2H_2 + O_2 = 2H_2O$$
$$CH_4 + 2O_2 = CO_2 + 2H_2O$$
$$C_2H_4 + 3O_2 = 2CO_2 + 2H_2O$$

Approximate Calorific Value.

Solid and Liquid Fuels.

If C, H, O, and S represent percentage composition by weight

Higher calorific value

$$= 14{,}540\,C + 62{,}100\left(H - \frac{O}{8}\right) + 4000\,S. \quad \text{B.Th.U. per lb.}$$

$$= 8080\,C + 34{,}500\left(H - \frac{O}{8}\right) + 2220\,S. \quad \text{C.H.U. per lb.}$$

Gaseous Fuels.	H.C.V. per cu. ft. (B.Th.U.)	(C.H.U.)
Hydrogen	345	192
Carbon monoxide . . .	340	189
Marsh gas	1050	585
Olefiant gas	1670	928

(*Note.* Accurate determination of calorific value is only possible by direct experiment in a calorimeter.)

Estimation of Approximate Weight of Air Supplied per lb. of Fuel.

C = percentage weight of carbon per lb. of fuel.

If N, CO_2, and CO represent percentage composition of dry flue gas by *weight*,

$$\text{Wt. of air per lb. of fuel} = \frac{N}{21CO_2 + 33CO} \times C.$$

If N, CO_2 and CO represent percentage composition of dry flue gas by *volume*,

$$\text{Wt. of air per lb. of fuel} = \frac{N}{33\,(CO_2 + CO)} \times C.$$

Heat Loss Due to Incomplete Combustion.

$$\text{B.Th.U. per lb.} = C \times \frac{CO}{CO + CO_2} \times 10{,}200.$$

Chimney Draught.

H = height of chimney in feet.

w = weight of air per lb. fuel.

h = draught in inches of water.

T_p = absolute temperature of gases in chimney.

Chimney Draught (*contd.*)

T_a = absolute temperature of air outside chimney (ashpit).

G_p = density of gases in chimney at T_p ° F. *abs.*

G_a = density of air outside chimney at T_a ° F. *abs.*

$$G_p = \frac{w+1}{12{\cdot}39w} \times \frac{492}{T_p}.$$

Draught pressure = P lb. per sq. ft. $= H(G_a - G_p)$

$$= \frac{492}{12{\cdot}39} H \left(\frac{1}{T_a} - \frac{w+1}{w} \cdot \frac{1}{T_p} \right)$$

$$= 5{\cdot}2\,h.$$

Neglecting increased density due to products of combustion (i.e. assuming contents of chimney to be pure air),

$$H = 0{\cdot}13h \frac{T_p T_a}{T_p - T_a}.$$

Theoretical velocity of flow of air $= \sqrt{4148h}$ f.p.s.

Stefan's Law.

Heat radiated from a black incandescent body

$= 16 \times 10^{-10}\ T^4$ B.Th.U./sq. ft./hour

$= 9{\cdot}33 \times 10^{-9}\ T^4$ C.H.U./sq. ft./hour.

Heat Transmission Through Flat Plate.

H = heat transmitted.

K = coefficient of conductivity.

$$H = K \times \frac{\text{Area} \times \text{Temperature difference} \times \text{Time}}{\text{Thickness}}$$

Heat Transmission from Fluid to Metal.

H = heat transmitted per degree difference of temperature of fluid and metal, per unit area per unit time.

v = velocity of flow of fluid over surface.

ρ = density of fluid.

A and B = constants depending on the nature of the fluid.

$H = A + B\rho v$. (Osborne Reynolds.)

Mean Temperature Difference Between Two Fluids.

θ_i = initial difference of temperature.

θ_o = final difference of temperature.

t_m = mean temperature difference.

$$t_m = \frac{\theta_i - \theta_o}{\log_e \frac{\theta_i}{\theta_o}}.$$

AIR COMPRESSORS

(1) *Single Stage.*

Compression curve $PV^n = C$.

$$\text{Work done per lb.} = \frac{n}{n-1} KT_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right]$$

Compression curve $PV = C$. Work done per lb. $= KT_1 \log_e \frac{P_2}{P_1}$

$$\text{Efficiency} = \frac{\text{Work done if compression isothermal}}{\text{Actual work done.}}$$

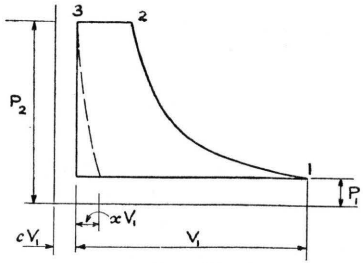


FIG. 15

Effect of Clearance (dotted line).

$$\text{Volumetric efficiency} = 1 - x = 1 - c \left\{ \left(\frac{P_2}{P_1} \right)^{\frac{1}{n}} - 1 \right\}$$

(2) *Two Stage.*

$$\text{Work done per lb.} = W = \frac{n}{n-1} KT_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} + \left(\frac{P_3}{P_2} \right)^{\frac{n-1}{n}} - 2 \right]$$

For minimum work $P_2 = \sqrt{P_1 P_3}$

$$W_{min} = \frac{2n}{n-1} KT_1 \left[\left(\frac{P_3}{P_1} \right)^{\frac{n-1}{2n}} - 1 \right]$$

(Similar expressions apply to 3-stage compression.)

Measurement of Air Flow.

Air passed through an orifice, area A sq. ft. and having a coefficient of discharge C. The pressure difference across the orifice, $(P_2 - P_1)$ lb. per sq. ft., is measured

If $\frac{P_1}{P_2} = r$ and the air expands according to the law $PV^n = C$.

$$\text{Mass flow} = \text{C.A.} \sqrt{2g \frac{n}{n-1} \frac{P_2}{V_2} \left(r^{\frac{2}{n}} - r^{\frac{n+1}{n}} \right)} \text{ lb. per sec.}$$

Normally $P_2 - P_1$ is small and $r = 1$ and $V_2 = V_1$ approximately.

$$\text{Mass flow} = \text{C.A.} \sqrt{\frac{2g(P_2 - P_1)}{V_1}} \text{ lb. per sec.}$$

Air Motors.

Air expanding from pressure P_2 to P_1.

(1) *Single Stage.*

$$\text{Work per lb.} = KT_2 \frac{n}{n-1} \left[1 - \left(\frac{P_1}{P_2} \right)^{\frac{n-1}{n}} \right]$$

(2) *Two Stage.*

(Intermediate re-heating to original temperature at pressure $Pr = \sqrt{P_1 P_2}$.)

$$\text{Work per lb.} = KT_2 \frac{2n}{n-1} \left[1 - \left(\frac{P_1}{P_2} \right)^{\frac{n-1}{2n}} \right]$$

REFRIGERATION

Q_2 = Heat taken in from cold body at temperature T_2.

Q_1 = Heat delivered from machine at higher temperature T_1.

Ideal coefficient of performance (reversed Carnot cycle)

$$= \frac{\text{Heat extracted}}{\text{Work expended}}$$

$$= \frac{Q_2}{Q_1 - Q_2} = \frac{T_2}{T_1 - T_2}$$

Bell-Coleman Machine. (Fig. 16.)

$$\text{Coefficient of performance} = \frac{T_d}{T_a - T_d} = \frac{T_c}{T_b - T_c}$$

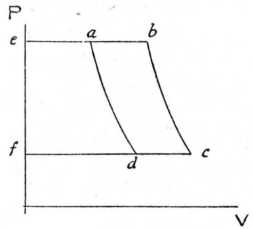


FIG. 16

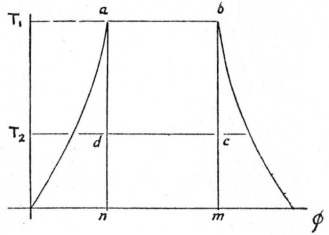


FIG. 17

Vapour Compression Machine with Expansion Cylinder. (Fig. 17.)

$$\text{Coefficient of performance} = \frac{\text{Area } dcmn}{\text{Area } dcba}$$

$$= \frac{T_2}{T_1 - T_2} \left(\begin{array}{l} \text{Whether the vapour is} \\ \text{dry or wet at the end} \\ \text{of compression.} \end{array} \right)$$

Vapour Compression Machine with Expansion Valve.

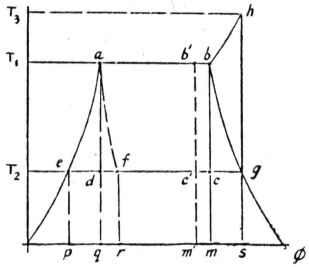


FIG. 18

During the free expansion (af) through the valve the heat in the refrigerant is constant.

$$\text{Area } efrp = \text{Area } peaq$$

$$ef = \frac{s(T_1 - T_2)}{T_2}.$$

(s = specific heat of liquid refrigerant.)

$$\text{Coefficient of performance} = \frac{\text{Heat abstracted}}{\text{Work done}}$$

$$= \frac{\text{Area } fc'm'r}{\text{Area } eab'c'} = \frac{sT_2 \log_e \frac{T_1}{T_2} + \frac{q_1 L_1}{T_1} \cdot T_2 - s\,(T - T_2)}{(T_1 - T_2)\left(s + \frac{q_1 L_1}{T_1}\right) - T_2 \cdot s \cdot \log_e \frac{T_1}{T_2}}$$

If vapour is just dry and saturated at end of compression,

$$\text{Coefficient of performance} = \frac{\text{Area } fcmr}{\text{Area } eabc}$$

($q_1 = 1$ in above expression.)

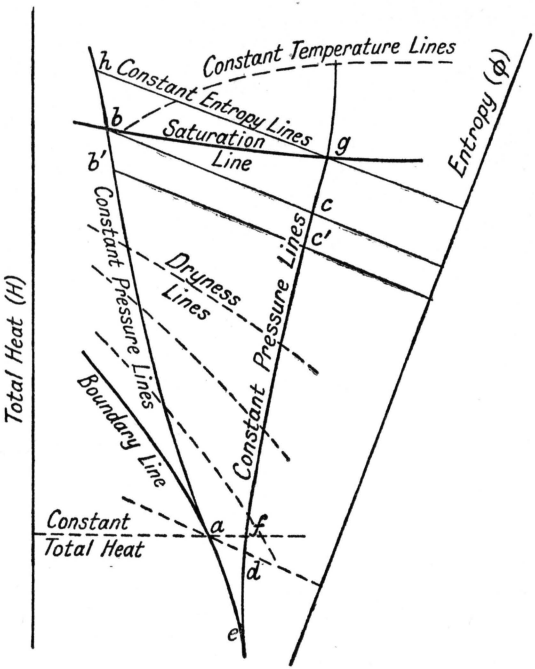

Total Heat (H)
Constant Temperature Lines
h
Constant Entropy Lines
b
Saturation Line
g
Entropy (ϕ)
b'
c
c'
Constant Pressure Lines
Dryness Lines
Constant Pressure Lines
Boundary Line
Constant Total Heat
a
f
d
e

FIG. 19

If dry and saturated vapour is drawn in from refrigerator (superheating to T_3),

Coefficient of performance

$$= \frac{L_2 - s\,(T_1 - T_2)}{(T_1 - T_2)\left(s + \frac{L_1}{T_1}\right) + c_m\,(T_3 - T_1) - T_2\left(s \log_e \frac{T_1}{T_2} + c_m \log_e \frac{T_3}{T_1}\right)}$$

Fig. 19 shows the corresponding "skew" diagram in which the cycle is exhibited more clearly by the use of oblique co-ordinates.

cb represents adiabatic compression (*gh* if superheated, *c'b'* if wet).

ba represents condensation.

ad represents adiabatic expansion (expansion cylinder).

af represents throttling (expansion valve).

fc represents refrigeration.

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